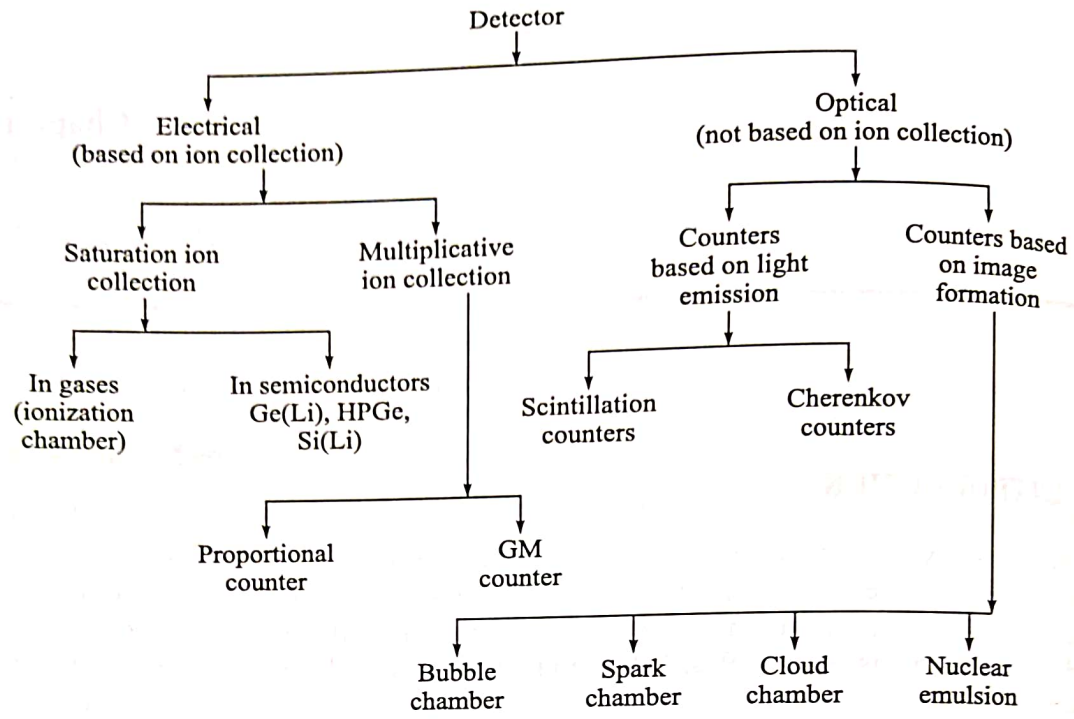

Figure 7.1 Classification of detectors according to signals produced.

excitation of electrons in the matter. In ionization the incident particle transfers an amount of energy equal to the ionization energy of the atom/molecule to permit the ionization process to occur. In this process an ion–electron pair is created. In most of the materials used for radiation detectors, the ionization energy for the least tightly bound electron is between 10 eV and 20 eV.

In excitation process, an electron is elevated to a higher bound state in the atom/molecule without completely removed. Later on, the excited electron may emit visible light and return to its original state.

In this chapter, we shall discuss the following radiation detectors:

1. Gas-filled detectors:
   (i) Ionization chamber.
   (ii) Proportional counter.
   (iii) Geiger–Müller (GM) counter.
2. Scintillation detectors.
3. Solid state detectors.

At the end of this chapter, some specialized detectors such as bubble chamber, spark chamber, cloud chamber, nuclear emulsions, etc. are discussed briefly. First *gas-filled detectors* are discussed.

7.2 GAS-FILLED DETECTORS

Gas-filled detectors are some of the oldest and most widely used detectors for nuclear radiations.

The reason for this is that they are very simple and relatively cheaper than most of other detectors. They can be fabricated and made in any size and shape in the laboratory itself. They are relatively free from radiation damage.

In the simplest form, a gas detector consists of a suitable gas enclosed in a container in which an electric field is applied by means of two parallel plate electrodes, one anode and other cathode.

7.2.1 Principle

They are based on the principle of ionization and excitation caused by charged particles while passing through a gas.

A schematic diagram of a gas-filled detector is shown in Figure 7.2.

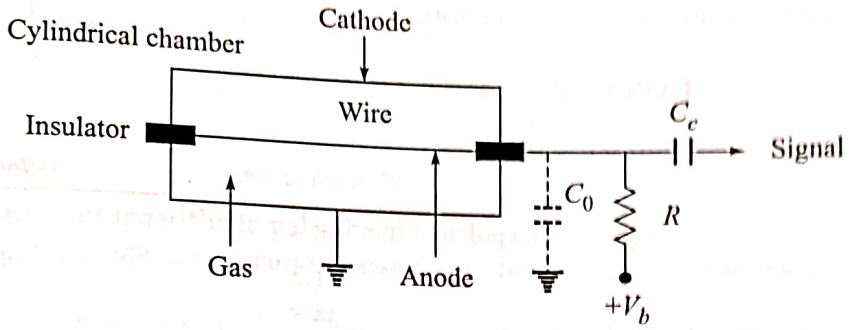

Figure 7.2 Schematic diagram of a gas-filled detector.

7.2.2 Construction and Working

It consists of a cylindrical gas-filled chamber. A thin wire is placed along its axis and is well insulated from the walls of the chamber. Through an external resistance R a positive potential is applied to the central wire, which acts as anode. The cylindrical chamber is grounded and it acts as a cathode. Capacity of the electrodes and stray capacities of the connecting wires, etc. constitutes the total capacity C_0 as shown in Figure 7.2. When a nuclear radiation (like electrons, α-particles, etc.) enters the chamber, it ionizes the gas present in the chamber thus creating number of positive ions and electrons called *ion-pairs*. If there is no electric field present, i.e. $V_b = 0$, the ion-pairs just created recombine forming neutral atoms/molecules. In the presence of the applied electric field ($V_b > 0$), the positive ions move along the radial electric lines of force i.e. towards the cathode or outer walls of the chamber. Similarly, electrons move towards the anode or central wire. Electrons being lighter than positive ions move at a much higher drift velocity ($\sim 10^6$ cm/s). The net effect of this is that a charge Q gets collected on the anode, and this charges the capacitor C_0 to a potential of Q/C_0. This change in the potential drops across R and gives rise to an electric pulse. Thus, when a charged particle passes through the gas present in the detector, the detector gives rise to a pulse, which is processed by external electronic circuit.

7.2.3 Concept of Average Energy Required for Creating Electron–Ion Pair (*W*-value)

We have already stated that a charged particle interacts with gas either through ionization or excitation. In ionization an electron–ion pair is created. The electrons so liberated when they reach the anode give information that a radiation has entered the detector. In excitation no such pair is formed. The energy consumed in excitation is wasted, as during excitation no electron reaches the anode. Therefore, the average energy lost by the incident particle in creating one ion-pair (defined as W-value) is always greater than the ionization energy of that gas. The W-value is a function of the gas present in the detector, type of radiation and its energy. However, experiments show that W-value is not a strong function of any of these parameters. Table 7.1 shows ionization potential I_p and W-value for fast electrons and α-particles for some of the commonly used gases in the radiation detectors.

TABLE 7.1 I_p and W-values for some gases

Gas	I_p (eV)	W (eV/ion-pair)	
		Fast electrons	*α-particles*
H_2	15.6	36.5	36.4
He	24.5	41.3	42.7
N_2	15.5	34.8	36.4
Ar	15.7	26.4	26.3
Air	–	33.8	35.1
CH_4	14.5	27.3	29.1

In most of the cases W lies between 25 eV and 35 eV per ion-pair.

Let us calculate the number of ion-pairs created, when a radiation of particular energy passes through a given gas. Suppose, 1 MeV α-particle is completely stopped within the gas with W-value = 30 eV/ion-pair. Then, the number of ion-pairs created

$$= \frac{10^6 \text{ eV}}{30 \text{ eV/ion-pair}}$$

$$\approx 33{,}000 \text{ ion-pairs}$$

If 3 MeV α-particle is completely stopped within the gas, it creates = $3 \times 33{,}000 \approx 99{,}000 \approx 1{,}00{,}000$ ion-pairs. This shows that the energy deposited by the incident radiation is directly proportional to the number of ion-pairs created. Hence, there is a possibility of determining the energy of incident radiation, if we can determine the number of ion-pairs created.

The variation of the logarithm of the number of ion-pairs formed or pulse height, which is across the resistor R, with applied voltage V for a gas detector is sketched in Figure 7.3. Two curves are shown in the figure corresponding to two different amount of energies brought in the gas. Lower curve marked as E_1 is for less-energetic particles while the upper curve marked as E_2 is for higher energy particles entering the gas detector. In the diagram symbols (o and Δ) are the measured values and line through the points is only a guide for the eye. Both these curves have

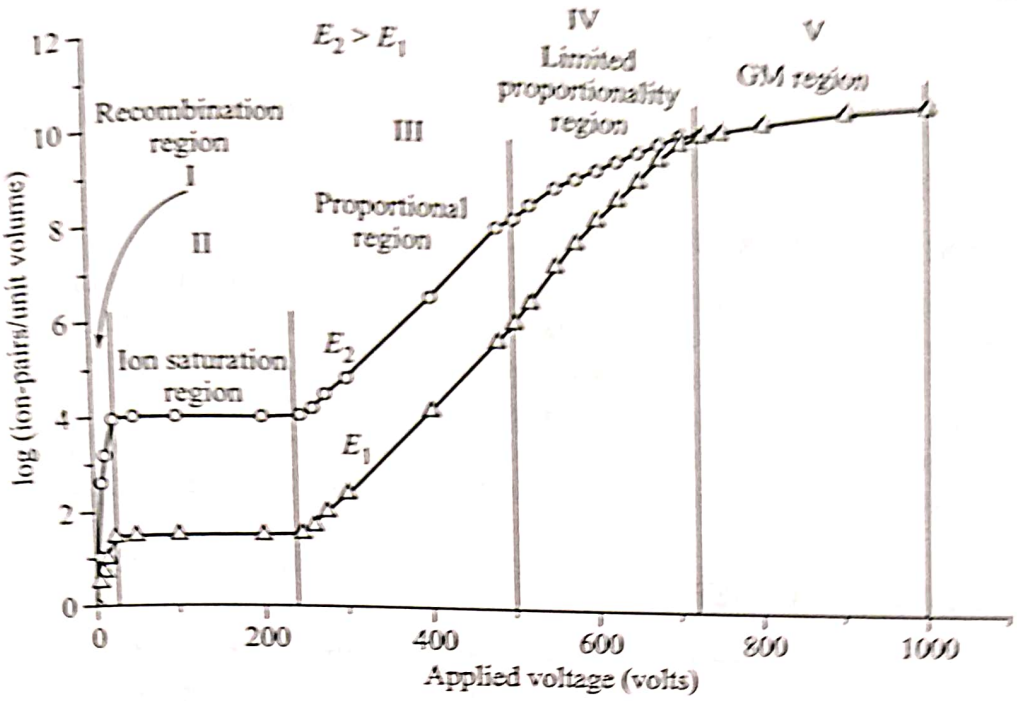

Figure 7.3 Variation of logarithmic pulse height or logarithm of number of ion-pairs formed versus applied voltage. Lower curve marked E_1 is for less energetic particles.

been drawn when the pressure inside the chamber is about 0.5 torr (1 torr = 1 mm of Hg) and the spacing between anode and cathode is 5 mm. In this diagram there are five regions marked as I, II, III, IV and V. Details of various regions are given as under.

Region I (~0 V *to* ~30 V)

In this region, the applied voltage is not sufficient to overcome the recombination of ion-pairs formed. As voltage is increased from 0 V to 30 V, more and more electrons start reaching the central anode and hence the pulse height is increasing in this region.

Region II (~30 V *to* ~250 V)

In this region, the curves are almost flat which signifies the collection of all the ion-pairs formed initially. Depending upon the energy of incident radiation about 10^1 to 10^4 ion-pairs are formed in this region due to primary radiation and they all are collected by the respective electrodes resulting in flattening of the curve. This region is known as *ionization region* and detectors operating in this region are called *ionization chambers*. The output pulses produced are of low amplitude, of the order of few mV.

Region III (~200 V *to* ~500 V)

Here, the production and collection of the ion-pairs increase rapidly with the applied voltage (this phenomenon is known as *gas multiplication* and is discussed later on). So, as long as the curves remain approximately parallel, the charge collected is proportional to the amount of the charge produced in the initial event which in turn is proportional to the energy of the incident radiation. This region is known as *proportional region* and the detectors operating in this region are known as *proportional counters*.

Region IV (~500 V to ~700 V)

In this region, larger amount of ionization is produced, but with less discrimination between the ion-pairs due to two different energy radiations. This region is known as *region of limited proportionality* and generally no detector operates in this region.

Region V (~800 V to ~1000 V)

In this voltage range, there is approximately flat region, also known as plateau and the number of ion-pairs formed per unit volume is ~10^9 to 10^{10}. This number is independent of the amount of initial ionization. This region is known as Geiger–Müller region and detectors operating in this region are known as *Geiger–Müller counters* or simply *GM counters*.

As is evident from the discussion above there are three gas-filled detectors, namely ionization chambers, proportional counters and GM counters. Now, we discuss them one by one.

7.3 IONIZATION CHAMBER

An ionization chamber is an instrument to measure the number of ions within a medium usually gas or air. It consists of a gas-filled enclosure between two conducting electrodes.

When the gas between the electrodes is ionized by some means such as alpha particles, beta particles, X-rays, or other radioactive emission, the ions move to the electrodes of opposite polarity, thus creating an ionization current which may be measured by a galvanometer or electrometer.

Ionization chambers are widely used in many fields since they provide an output that is proportional to dose and have a greater operating lifetime than standard Geiger tubes (in Geiger tubes, the gas eventually breaks down).

7.3.1 Principle

The ionization chamber works on the principle that charged particles passing through the matter remove electrons from the atoms as they move along (process called ionization). If voltage is applied across the material that is ionized, the electrons drift to one side and the leftover positively charged ions drift to the other.

7.3.2 Construction

Schematically an ionization chamber is shown in Figure 7.4. It is in the form of a rectangular box. It consists of two parallel plate electrodes separated by a distance d. These electrode combinations form a capacitor with capacity C. High voltage is applied across these plates through a large bias resistance R. This voltage sets up an electric field across the two plates. These plates are enclosed in a chamber and the chamber is filled with a desired gas. The most common gas in ionization chamber is air. Other gases used in such a detector are He, Ne, isobutene, etc. In some cases, ionization chamber is of cylindrical shape. The cylinder is made up of conducting metals like copper which acts as cathode. A straight thin wire passes in the centre of the cylinder and is isolated from it. It acts as anode.

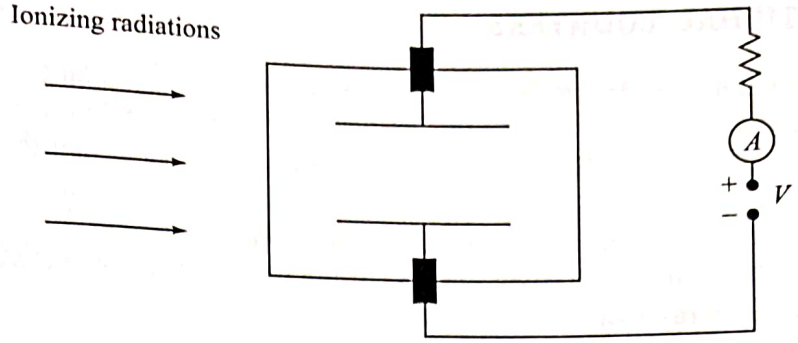

Figure 7.4 Ionization chamber.

7.3.3 Working

When incident radiations enter the ionization chamber, they ionize the gas present in the chamber, producing electrons and positive ions together known as electron-ion pairs. Under the influence of the electric field, electrons and ions move towards their respective electrodes. For a voltage gradient of 100 V cm^{-1}, ions at a speed of about 1 m/s in air at STP take about 0.02 s to cross a gap of ~2 cm. Electrons being lighter move about 1000 times faster and are collected at anode quickly. The slow movement of positive ions means that the ionization chamber is inoperative till all the +ve ions get neutralized at the cathode.

The electrons collected at anode constitute a current in the circuit. The number of electron-ion pairs produced in the gas and hence the current in the circuit is calculated as under.

Consider that a 3.5 MeV α-particle is moving in an ionization chamber, filled with air. Air has W-value ~35 eV. This α-particle produces

$$\sim \frac{3.5 \times 10^6}{35} \approx 10^5 \text{ ion-pairs.}$$

Let us suppose that the source is emitting about 10^4 α-particles per second. These particles will produce a current of

$$1.6 \times 10^{-19} \times 10^5 \times 10^4 \approx 1.6 \times 10^{-10} \text{ A}$$

This current, though small, can be measured with most of the current meters.

7.3.4 Main Uses

Ion chambers have a good uniform response to radiation over a wide range of energies and are the preferred means of measuring high levels of gamma radiation. They are widely used in the nuclear power industry, research labs, radiography, other medical radiation fields, and in environmental monitoring.

They are also used as radiation survey instruments, for calibrating or measuring the activity of radioactive sources, measuring radioactive gases, etc.

7.3.5 Main Drawback

These detectors are not suitable to measure individual particles entering the chamber at a higher rate.

7.4 PROPORTIONAL COUNTERS

A proportional counter is a device to count particles of ionizing radiation and measure their energy. It works on the same principle as the Geiger–Müller counter, but uses a lower operating voltage. A proportional counter differs from an ionization chamber in that the operating voltage is sufficiently high that the drifting electrons gain enough energy over a mean free path to create further ion-pairs when they collide with other neutral atoms of the gas.

By measuring the total charge (time integral of the electric current) between the electrodes, the particle's kinetic energy can be calculated.

7.4.1 Principle

Proportional counters use the principle that nuclear radiations while passing through a medium ionize the medium.

7.4.2 Construction

The proportional counter is another gas-filled detector that was introduced in the late 1940s. These detectors work in the proportional region III (Figure 7.3). The proportional counters are available in a variety of shapes and sizes. The most commonly used proportional counters are cylindrical in shape. The cylinder is made up of metal, which acts as a cathode. In some cases, this cylinder is made up of glass, the inner walls of which are coated with a conducting metal like copper or silver. In the centre of the cylindrical cathode, a straight conducting wire, which is insulated from the outer cylinder, acts as anode. The schematic view of the proportional counter is shown in Figure 7.5. Usually a mixture of gases is used containing gases like neon, argon, krypton, etc. which favor high amplification and a complex gas like carbon dioxide, methane, pentane etc., which helps in stopping the phenomenon of secondary ionization. Common proportional counters used in the laboratories contain a mixture of about 90% argon and 10% methane. The total gas pressure in the tube is generally less than one atmosphere. A thin glass, mica or polymer window (~10 μm) isolates the gases present in the proportional counter from the atmosphere.

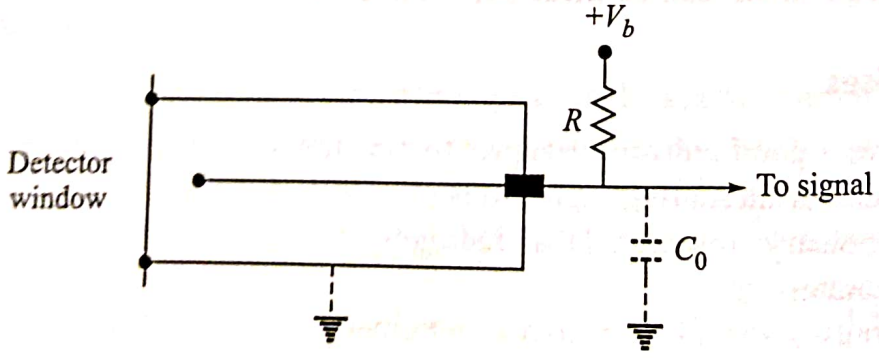

Figure 7.5 Schematic diagram of a proportional counter.

7.4.3 Working

As discussed earlier, the output current signal in the ionization chambers is very low. One common method of amplifying the signal is to increase the electric field till electrons gain sufficient energy between two successive collisions with gas atoms to cause further ionization.

A high voltage (V) applied to anode is so adjusted that the tube operates in the proportional region (Figure 7.3). For cylindrical geometry, the strength of electric field at a radial distance r from the central wire is given by

$$E(r) = \frac{V}{r \log\left(\frac{b}{a}\right)}$$

where a and b are the radii of the central wire and the inner radius of the cylinder, respectively. The electric field in the neighbourhood of anode wire is extremely high. For example, if $a = 0.005$ cm, $b = 1.0$ cm, and $V = 2000$ V, then

$$E(r) = 5.18 \times 10^6 \text{ V/m near the wire.}$$

In proportional counters, cylindrical geometry is preferred. For parallel plate geometry when spacing between the plates is 1 cm, then to get this field gradient, voltage of about 51,800 V is required for this field gradient. This is practically unworkable.

In such a high electric field gradient, a phenomenon called *gas multiplication* sets in. This can be explained as under.

Gas Amplification

Because of the increasing voltage, the electrons librated by the primary ionizing event get sufficient kinetic energy. These energetic electrons while moving towards the anode collide with neutral gas atoms, causing ionization of the neutral atoms. The electrons so produced may cause further ionization. This multiplication effect is often called a *Townsend avalanche* or *Townsend cascade*. The total number of ion-pairs produced by a single primary ion-pair is called the *gas multiplication factor*. This factor is unity in ionization chamber and is 10^2 to 10^4 in proportional counters. For example, if 10^4 ion-pairs are originally created by the incident particle and are multiplied by a factor of 1000, then instead of 10^4 pairs now the detector has 10^7 ion-pairs.

At such a high field, the electrons acquire sufficiently high velocities. For example, if the field gradient is 10^4 V m^{-1}, the velocity of the electrons is approximately 4×10^4 m/s. With such high velocities, electrons generated near the cathode take less than 1 μs to reach the anode. Thus, the proportional counter works at a much faster rate compared to the ionization chamber.

A proportional counter has two main features. First because of its built-in amplification, it can conveniently detect low energy radiations and second because of its proportionality, one can produce an energy spectrum of the incoming radiations.

Figure 7.6 shows a typical low energy X-ray spectrum obtained with a proportional counter. This shows two peaks, first at 22.1 keV due to K_α line of Ag and second at 25.0 keV due to K_β line of Ag. One important parameter used in such detectors is Energy Resolution or Full Width

at Half Maximum (FWHM). From the experimental spectrum, it is measured as under. Let us consider 22.1 keV peak. The maximum counts at this peak are 2000. The width of the peak at exactly half of 2000, i.e. 1000 counts, is about 1300 eV. This number 1300 eV is known as energy resolution or FWHM of this detector at 22.1 keV. The physical meaning of energy resolution is that if there are two peaks with energy difference greater than the resolution, the peaks are seen as two separate peaks; otherwise only a single peak is visible. For example, in the present detector where the energy resolution is 1300 eV, if we draw the spectrum with two X-rays at 22.1 the and 22.2 keV, the detector shows only a single peak.

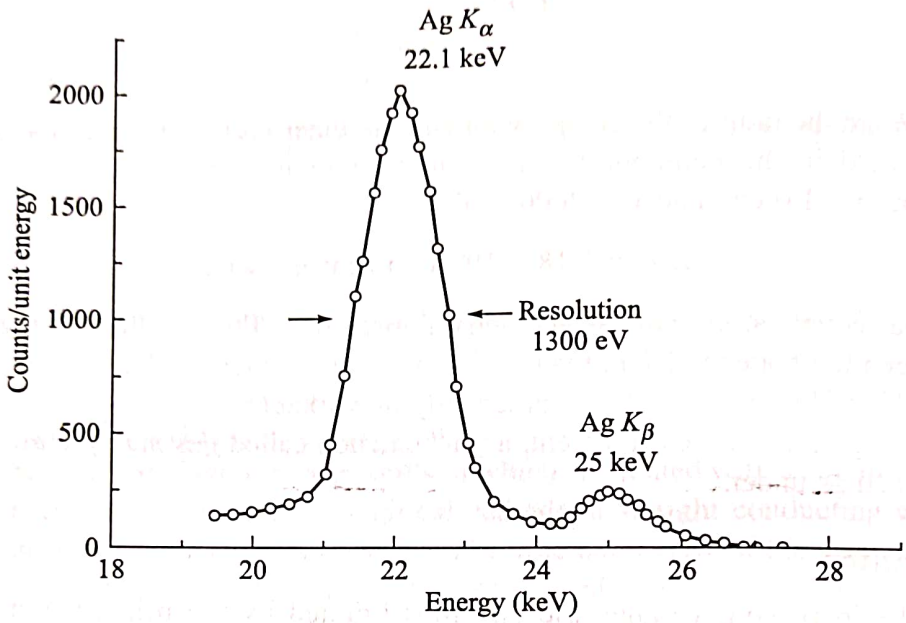

Figure 7.6 X-ray spectrum of Ag having two X-rays at 22.1 keV and 25.2 keV recorded with proportional counter.

7.4.4 Uses

The main use of proportional counters is detecting charged particles and low energy X-rays and recording their energy spectrum. $^{10}BF_3$-filled proportional counters are used for detecting slow neutrons. Slow neutrons produce $^{10}B(n, \alpha)^7$ Li reaction. α-particles ejected in the reaction are detected in the proportional counter.

7.4.5 Main Disadvantage

The main disadvantage of the proportional counter is the need for an expensive highly stabilized power supply to maintain the proportionality characteristics.

7.5 GEIGER–MÜLLER (GM) COUNTERS

If we continue to increase the voltage across the electrodes (Figure 7.3), then we pass from the proportional region through the region of limited proportionality to the GM region. In this case,

the electron cascade spreads from the immediate neighbourhood of the initial track, until it encompasses the whole length of the anode. The resulting pulse is thus very much larger than that obtained from a proportional counter, but is obviously independent of the initial particle energy. This means that all pulses from a GM tube are of the same amplitude regardless of the number of original ion-pairs that started the process or is independent of the energy brought into the tube by the incident particle. Therefore, a GM counter cannot be used for measuring energy of the radiations.

This counter was named after Hans Geiger and W. Müller, who invented it in the 1920s. It is sometimes called a Geiger counter or a GM counter or GM tube and is the most commonly used portable radiation instrument. Although useful, cheap and robust, a counter using a GM tube can only detect the presence and intensity of radiation. Geiger counters are used to detect ionizing radiation, usually alpha and beta radiation and other types of radiation like low energy X-rays, etc.

7.5.1 Principle

It works on the principle that nuclear radiations while passing through the gas contained in GM counter ionize it.

7.5.2 Construction

The schematic diagram of a GM counter is identical to that of a proportional counter and is shown in Figure 7.5. In majority of the cases, The GM tube is cylindrical in shape. This cylinder is either made up of a conducting metal like copper, which acts as a cathode or it is made up of glass, in which a metallic cylinder is supported, which acts as a cathode. However, in some cases when the tube is of glass, inner sides of the tube are coated with a conducting metal like copper or silver. This coating acts as a cathode. Anode is generally made up of tungsten wire which stretches in the centre of the tube and is isolated from the cylindrical tube. The thickness of this wire is generally 0.02 to 0.05 mm.

Depending upon the requirement, the GM tubes are available in a variety of sizes. The diameters of the tubes vary from 0.3 cm to about 15 cm while their lengths vary from 1 cm to 100 cm.

Commercially available GM tubes are filled with 90% argon (as the filling gas) and 10% ethyl alcohol (as the quenching gas) or 0.1% either chlorine or bromine (as the quenching gas) and the rest is neon or argon gas. A thin glass, mica or polymer window (~10 μm) isolates the gases present in the GM counter from the atmosphere.

7.5.3 Working

The charged particles entering the GM tube ionize the gas present in the tube. This event is known as *primary ionization*. The electrons librated in the primary ionization are accelerated towards the central anode wire. Because of high potential present on the wire, the electrons may gain sufficient energy to cause further ionization of the neutral gas molecules (known as secondary ionization). This leads to a chain of ionizing events, which is already discussed and is known as Townsend avalanche.

Besides these processes, there is a possibility of excitation of molecules and atoms. Such excited molecules and atoms, while de-exciting, may emit ultra violet (UV) or visible photons. These photons again lead to the production of electrons due to ionization of gas atoms or molecules or due to photoelectric interaction with walls of the counter. Each such librated electron would again cause a Townsend avalanche. Such a series of avalanches would lead to discharge in the tube called Geiger discharge. In such a state, there is a formation of dense envelop of electron–ion pairs distributed around the anode. The voltage applied to anode collects all the electrons pertaining to single event leading to Geiger discharge.

Quenching

Practically the process is not as simple as discussed above. During the Geiger discharge, there is a dense envelop of ions and electrons around the anode. The electrons would drift towards the anode and positive ions would drift towards the cathode. The positive ions drifting towards the cathode having ionization potential greater than the work function of the cathode material lead to exchange of electron from the cathode and become neutral. The excess energy may be dissipated with the emission of either a photon or an electron from the cathode the latter process takes place only if excess energy is greater than the work function of the cathode material. This again initiates another Geiger discharge. The result of this is that the tube would always be in continuous Geiger discharge and hence is not able to measure any radiation.

To overcome this problem, the concept of quenching is introduced. There are two types of quenching:

1. Organic quenching
2. Halogen quenching

Organic quenching: This involves addition of small quantity of organic gas having a complex molecular structure. This prevents the continuous Geiger discharge by charge transfer collision principle. The positive ions on their path collide with organic molecules to get neutralized. This makes only ions of organic gas to reach the cathode and get neutralized. Any excess energy released would lead to dissociation of organic molecules. Thus, multiple Geiger discharge could be avoided.

A typical filling of organic quenched GM tubes is 90% argon and 10% ethyl alcohol. When the organic gas gets depleted to a sufficient extent, there is the occurrence of multiple discharges frequently and thus the plateau length gets decreased with slope increased.

The organic quenched GM tubes are characterized by short life time and are not suitable for operation in very high fields which leads to large count rate. To overcome this, the technique of halogen quenching was introduced.

Halogen quenching: This involves the addition of small quantity of halogen gas such as chlorine or bromine. A typical filling is about 0.1% of chlorine to argon or neon. The quenching action is the same as that of the organic quenching process. The diatomic halogen gas molecules also get dissociated in quenching but get recombined to replenish the gas molecules and thus the counter life gets extended.

Characteristics of GM Tubes

The important parameters which decide the quality of functioning of GM tubes are as follows:

1. Dead time
2. Recovery time
3. Geiger plateau length and plateau slope

Dead Time: As discussed above, the positive ions take considerable time to reach the cathode compared to electrons. The reason is that the mobility of electrons is about 1000 times greater than that of positive ions. Due to low drift velocity of positive ions, there is a formation of cloud of positive ions. The electric field of these positive ions forms a sheath of positive ions (space charge) close to the anode and reduces the intense electric field sufficiently. Thus, approaching electrons do not gain sufficient energy to start new avalanches. The detector is then inoperative (dead) for the time required for the ion sheath to migrate outwards far enough for the field gradient to recover above the avalanche threshold. The dead time of a Geiger tube is defined as the time between the initial pulse and the time at which a second Geiger discharge (regardless of its size) can be developed. In most Geiger tubes, this time is of the order of 50–100 μs.

Dead time is the time immediately following the introduction of a particle during which the counter tube is insensitive for detection of another particle.

Recovery time: After the dead time is over, some of the electrons and +ve ions recombine and form neutral atoms. During this time, when a new ionizing radiation enters the tube, pulses of lower amplitude are formed, which cannot be counted by the counter.

The total time taken for the tube to recover to its fully sensitive state to give the next pulse is called *recovery time*.

The sum of the *dead time* and *recovery time* is called *Resolving time*.

The dead time, recovery time and resolving time are shown in Figure 7.7. During the dead time, no new pulses are formed. However, during the recovery time, pulses of lower amplitude are formed, which are not counted by the counting system. It is only after the recovery time that the pulses of larger amplitude are formed, capable of getting counted.

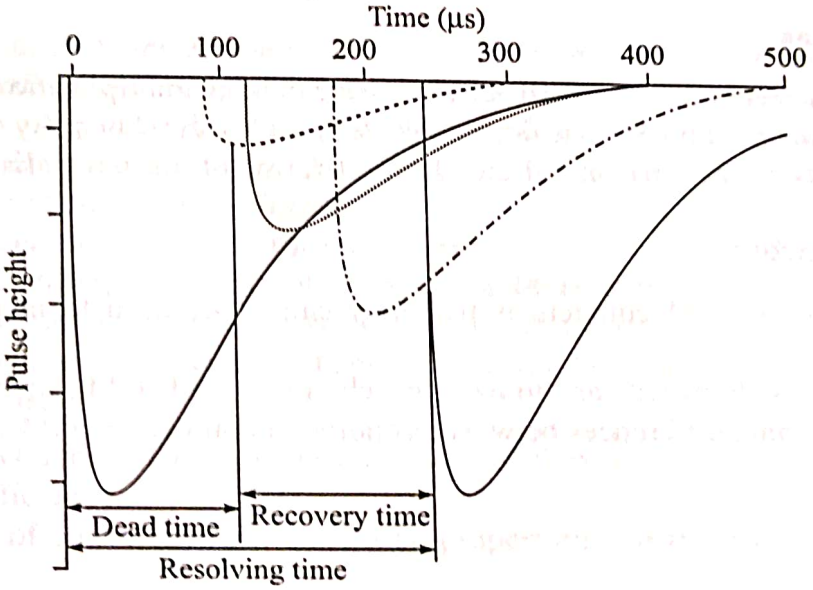

Figure 7.7 Relation between dead time, recovery time and resolving time of a GM counter.

Geiger plateau: In Figure 7.8, a plot of count rate versus the anode voltage is shown. In this figure, the source of radiations is kept at a fixed distance from the counter. The potential difference at which the counting just starts is called threshold potential. The typical threshold potential depends upon the gas and its pressure in the counter. It generally varies between 400 and 900 volts. After a very sharp rise, the counting rate remains almost constant with increasing voltage. *This flat region, the plateau, where the number of counts recorded per second remains independent of applied voltage is called Geiger region.* The length of the plateau is about 100 to 300 volts. When the plateau region becomes shorter and steeper, it means that the GM tube is nearing the end of its useful life. If a Geiger–Müllar counter is operated in this region, it eliminates the need of a costly and highly regulated power supply.

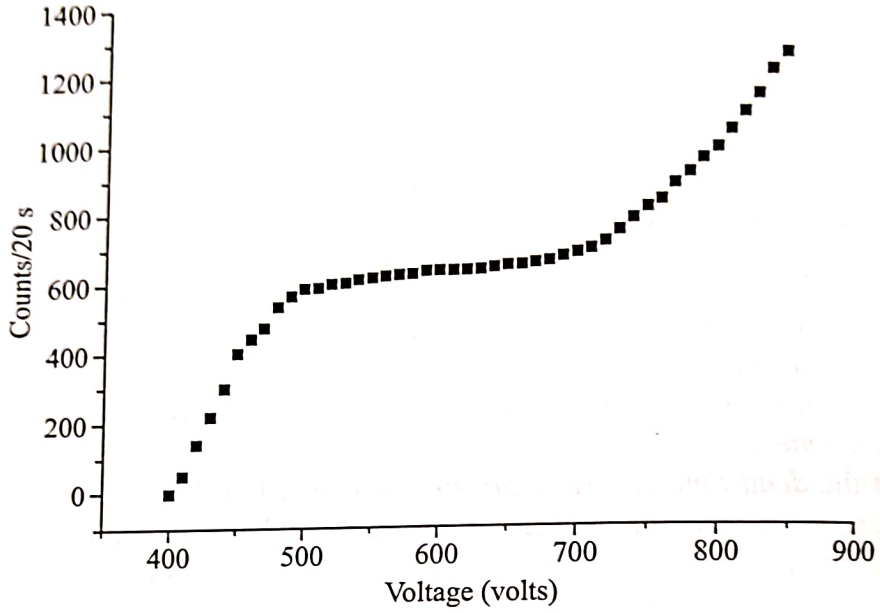

Figure 7.8 Plateau curve of a GM counter.

7.5.4 Main Uses

GM counters can detect even very small activities (due to large multiplication factor) and they are extensively used for detecting X-rays, β-particles, α-particles, etc. For γ-ray detection, we require bigger size GM tubes. They are one of the cheapest forms of nuclear radiation detectors.

7.5.5 Main Drawback

The major drawback of GM counters is that they cannot be used to measure the energy of radiations.

Main differences between an ionization chamber and GM counter are shown in Table 7.2, while the main differences between propotional counter and GM counter are shown in Table 7.3.

TABLE 7.2 Differences between ionization chamber and GM counter

S. No.	*Ionization chamber*	*GM counter*
1.	It operates in the ionization region (region II, Figure 7.3).	It operates in the GM region (region V, Figure 7.3).
2.	It operates at relatively low voltages (~ 30 V to ~ 250 V).	It operates at much higher voltages (~ 800 V to ~ 1000 V).
3.	The output pulse height is low, so an amplifier is needed.	The output pulse height is large, so no amplifier is needed.
4.	Power supply used to feed voltage to ionization chamber must be highly regulated.	Power supply used to feed voltage to a GM counter need not be regulated.

TABLE 7.3 Differences between proportional counter and GM counter

S. No.	*Proportional counter*	*GM counter*
1.	It works in the proportional region (region III, Figure 7.3).	It works in the GM region (region V, Figure 7.3).
2.	It generally operates at lower voltages (~200 V to ~500 V).	It generally operates at higher voltages (~ 800 V to ~1000 V).
3.	Output pulse height depends upon the energy of the incident particle.	Output pulse height do not depends upon the energy of incident particle.
4.	Energy of the incident radiation is measured by it.	Energy of the incident radiation cannot be measured by it. However, intensity/flux of incident radiation can be measured by it.
5.	The output pulse height is low, so an amplifier is needed.	The output pulse height is large, so no amplifier is needed.
6.	Power supply used to feed voltage to proportional counter must be highly regulated.	Power supply used to feed voltage to a GM counter need not be regulated.

7.6 SCINTILLATION DETECTORS

We are familiar with ZnS screen used by Rutherford in his famous α scattering experiment. α-particles, when fall on ZnS, produce light flashes or scintillations. These flashes can be seen with a microscope. ZnS was the first scintillation detector put to actual use. Another most common and familiar example of the use of scintillation mechanism is the television screen, which emits visible photons under electron bombardment in a cathode ray tube.

It was found later on that along with ZnS, there are a large number of materials which exhibit the property of scintillations. Some of them are sodium iodide, cesium iodide, anthracene, naphthalene, etc. Some gases particularly noble gases like xenon, etc. also exhibit this property.

Any material which fulfils certain characteristics can be used for this purpose. Some of the important characteristics are:

(a) It should convert energy of the incident radiation into visible light radiation with the highest efficiency.

(b) The yield of converted light should be proportional to the energy deposited inside the detector.

(c) For good light collection, the material should be transparent to its own light.
(d) The decay time of emitted light should be short.
(e) The refractive index of the material should be similar to glass for good coupling to photomultiplier tube.

Many materials, both solids and liquids fulfil these criteria and hence can be used as scintillators. Scintillation detectors became the most powerful and widely used radiation detectors with the development of photo multiplier (PM) tubes. These PM tubes are extremely sensitive detectors of light. Thus, there is no need of using a microscope to view the scintillations.

A scintillation spectrometer consists of three components:

1. Scintillation detector/crystal
2. Photomultiplier tube
3. Electronic circuitry

Below we discuss these components one by one.

7.6.1 Scintillation Detector/Crystal

Scintillators are available in many forms. Some commonly used scintillators are

1. **Inorganic crystals**
   - NaI(Tl): This is the most commonly used scintillator for γ-ray work. The efficiency for the conversion of the energy deposited into light output is one of the highest among all known scintillators. It is available in a variety of shapes and sizes. One drawback with this scintillator is that it is hygroscopic and therefore it has to be sealed in airtight containers. Another drawback of this scintillator is that its density is low (~ 3.67 g/cm^3).
   - CsI(Tl) and CsI(Na): These crystals are non-hygroscopic and have light output compared to that of NaI(Tl). The only difficulty with these scintillators is that growing big single crystals is quite difficult.
   - CaF_2(Eu): This again is a non-hygroscopic crystal and it is useful to detect low energy (<100 keV) X- or γ-rays.
   - ZnS: It was the first scintillator used in nuclear physics. However, making big transparent single crystals is quite difficult.
   - $Bi_4Ge_3O_{12}$ (BGO): It is non-hygroscopic, mechanically and chemically more durable compared to NaI(Tl). Its density is much larger (7.13 g/cm^3) than that of NaI(Tl) scintillator. This would enable us to use a smaller size crystal compared to NaI(Tl) crystal having the same efficiency. However, it has low light output and its energy resolution is inferior compared to that of NaI(Tl). They are more expensive than NaI(Tl) detectors.
2. **Organic scintillators:** Common organic scintillators are anthracence, stilbenek, etc. These scintillators have very poor efficiency compared to NaI(Tl) detector. However, in these scintillators, the decay time of light produced due to ionizing radiations is much shorter compared to that in NaI(Tl) detector. These detectors can be operated at higher count rate. These detectors are practically more suitable to β counting.

3. **Liquid scintillators:** In these detectors, scintillator material is dissolved in certain suitable liquid. In some applications, radioactive source is thoroughly mixed with liquid scintillator. These detectors are mostly used to count very low activities specially that of β-particles.

Many scientists have studied the mechanism of light emission by scintillators in detail. Without going into the detailed mechanism of light emission, certain terms commonly used while working with scintillation detectors are discussed.

The process by which visible light is emitted by the scintillator within 10^{-8} s of falling of radiations is known as *prompt fluorescence* or simply *fluorescence*. There is another mechanism of visible light emission known as *phosphorescence*, in which the light of longer wavelength is emitted and this process occurs in a time which is much longer (few seconds to few minutes). There is a third mechanism, which is known as *delayed fluorescence* in which the light emitted is of the same wavelength as in fluorescence but its emission time is longer (hours to days).

Another term commonly used in scintillators is the *scintillation efficiency*. It is defined as the fraction of the energy deposited by the incident radiation that is converted into light.

A good scintillator should have high scintillation efficiency and should convert a larger fraction of the emitted light by the process of prompt fluorescence. Single crystal of sodium iodide with traces of thallium written as NaI(Tl) is one such crystal, which is extensively used for detecting and measuring the energy of γ-rays. Tl in scintillators is also known as *wave length shifter*. The emission spectrum of pure sodium iodide has maxima at a wavelength of 303 nm. Most of the photomultiplier tubes are not sensitive to this wavelength. Addition of a small quantity of Tl (0.1 to 0.5% mole fraction of Tl) shifts this wavelength to 410 nm. Most of the photomultiplier tubes are sensitive to this wavelength.

Incident-charged particles falling on the scintillator lose all the energy in the scintillator and light photons are produced. However, if the incident radiations are X- or γ-rays, they interact with the scintillator in mainly three different ways (Chapter 5).

1. Photoelectric effect
2. Compton effect
3. Pair production

In all these three processes, electrons are produced and ultimately total energy of X- or γ-rays is converted into the kinetic energy of electrons. These electrons give up their kinetic energy in ionization and excitation in the scintillator material, resulting in production of scintillations in the scintillator.

Scintillators are available in a variety of shapes and sizes. Scintillators commonly used in laboratories have dimensions as $1'' \times 1''$ or $1\frac{1}{2}'' \times 1\frac{1}{2}''$. $1'' \times 1''$ means it is a cylinder of base diameter of $1''$ and height of $1''$, etc.

All the light produced in the scintillator should reach the photomultiplier tube. For this purpose, the scintillator is covered with light reflector MgO from all sides except one and this uncovered side is optically coupled to PM tube. Optical coupling means that the whole of the light photons produced in the scintillator reaches the photo cathode of the PM tube without any loss.

7.6.2 Photomultiplier Tubes

Photomultiplier tubes (PMTs) are extremely sensitive detectors of light in the ultraviolet, visible and near infrared. These detectors multiply the signal produced by incident light by as much as 10^6 to 10^8. The combination of high gain, low noise and large area of collection means that these devices find applications in nuclear and particle physics.

Photomultipliers are constructed from a glass vacuum tube which houses a photocathode, several dynodes and an anode as shown in Figure 7.9. Incident photons strike the photocathode of the PM tube, and electrons are produced as a consequence of the photoelectric effect. The photocathode is generally coated with either antimony-rubidium-cesium or antimony-potassium-cesium. These electrons are directed by the focusing electrode towards the electron multiplier, where electrons are multiplied by the process of secondary emission.

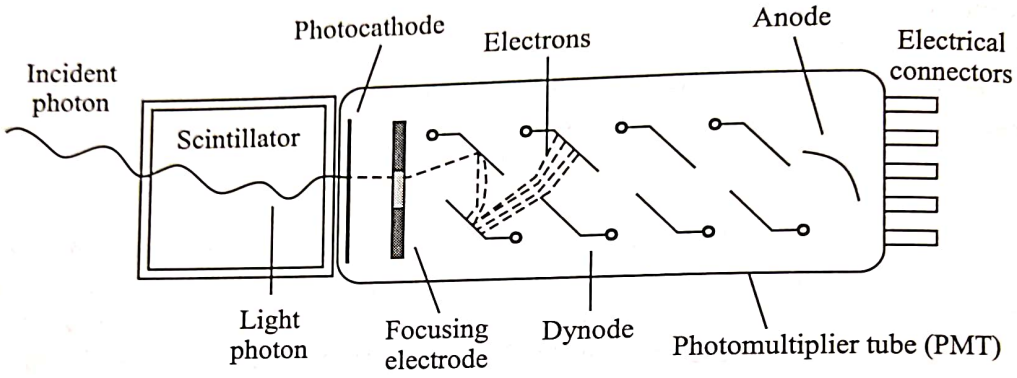

Figure 7.9 Photomultiplier tube.

The electron multiplier consists of a number of electrodes, called *dynodes*. Each dynode is held at a more positive voltage than the previous one (50 to 100 V). The electrons are ejected by the photocathode. As they move towards the first dynode, they are accelerated by the electric field and arrive with much greater energy. On striking the first dynode, more low energy electrons are emitted and these, in turn, are accelerated towards the second dynode. The geometry of the dynode chain is such that a cascade occurs with an ever-increasing number of electrons being produced at each stage. Finally the anode is reached where the accumulation of charge results in a sharp current pulse indicating the arrival of a photon at the photocathode.

7.6.3 Electronic Circuitry

A block diagram of a complete NaI(Tl) γ-ray spectrometer is shown in Figure 7.10. In this figure, pre-amp is a pre-amplifier. The purpose of the pre-amplifier is to match impedance between photomultiplier and amplifier. Amplifier amplifies the signal arriving at its input. The amplified output of the amplifier is in direct proportion to the energy deposited by γ-rays in scintillation detector. For example, if energy absorbed in the NaI(Tl) detector is 100 keV, the amplifier gives output pulse of 1 V (say) and if the energy deposited in the NaI(Tl) is 600 keV, the output pulse would be 6 V and so on. The SCA stands for single channel analyzer. It gives the number of pulses in a certain voltage interval, for example, the number of pulses between voltage interval 500 mV and 600 mV, etc., depending upon the setting of SCA. These pulses are fed to counter/timer, which counts the number of pulses for a fixed time. A typical γ-ray spectrum of ^{137}Cs

emitting one γ-ray of 662 keV is shown in Figure 7.11. The resolution of the scintillation spectrometer at 662 keV is 75 keV. Similarly the γ-ray spectrum of ^{60}Co emitting two γ-rays of 1172 and 1332 keV is shown in Figure 7.12. The two peaks are clearly visible in the spectrum.

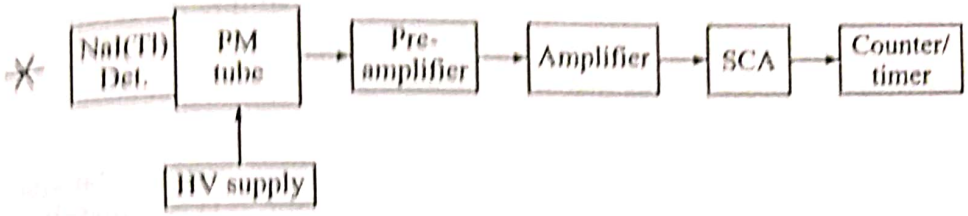

Figure 7.10 Block diagram of a scintillation spectrometer.

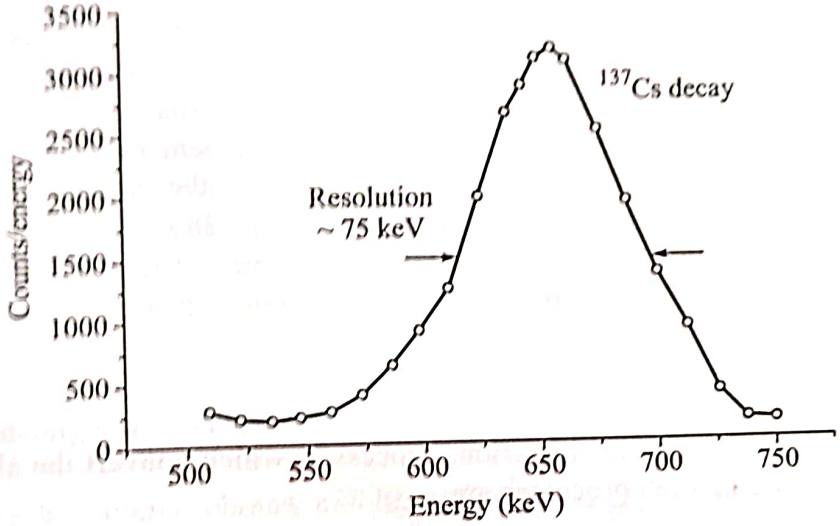

Figure 7.11 Photo peak (662 keV) of γ-ray spectrum of ^{137}Cs as recorded by a scintillation spectrometer. The photo peak shows an energy resolution of ~75 keV.

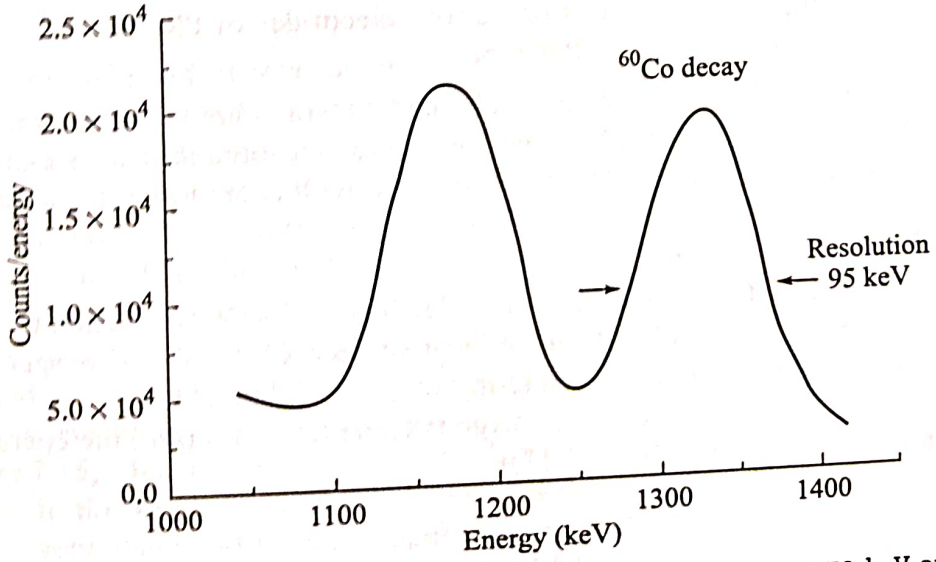

Figure 7.12 Photo peaks of γ-ray spectrum of ^{60}Co. It has two γ-rays of 1172 keV and 1332 keV.

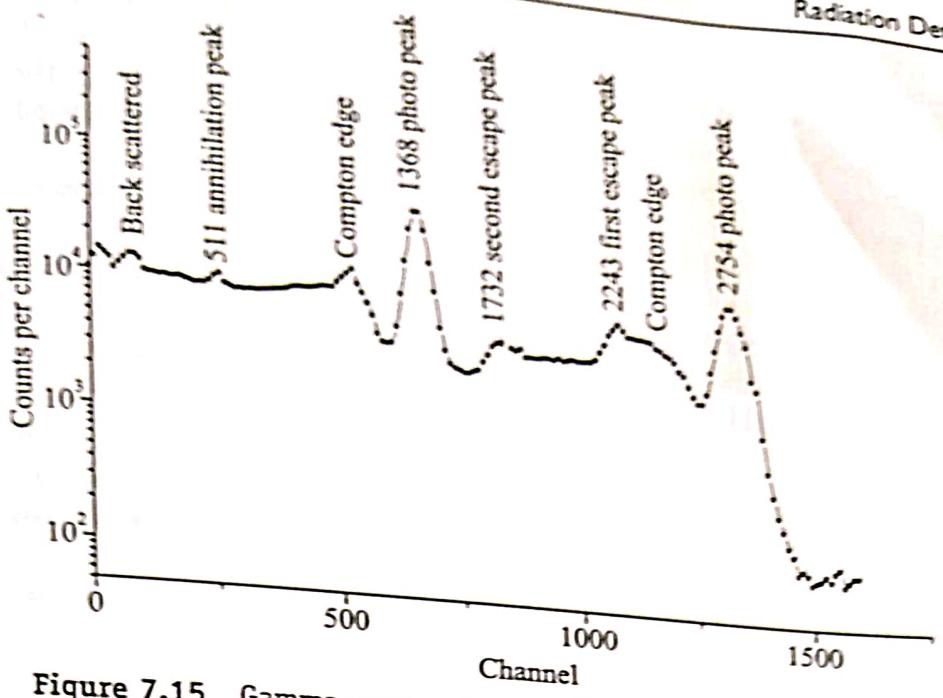

Figure 7.15 Gamma ray spectrum of ^{24}Na with NaI(Tl) detector.

7.6.4 Uses of Scintillation Detectors

- Inorganic scintillation detectors are used to measure the energy of X- and γ-rays.
- Organic scintillation detectors are used to detect β and α-particles.
- They generally have high efficiency. Efficiency is nearly 100% in case of NaI(Tl) detectors.
- They are rugged and can with mechanical jerks.
- Scintillation detectors have very short dead time ($\sim 10^{-9}$ s) permitting very high counting rates.

7.6.5 Limitations of Scintillation Detectors

- Energy resolution of these detectors is poor. For example, in case of NaI(Tl) detector, the energy resolution is 8–10% at 662 keV.
- The NaI(Tl) detector is hygroscopic. If it absorbs moisture, it is completely damaged.

7.7 SEMICONDUCTOR RADIATION DETECTORS

The field of nuclear physics has been completely revolutionalized with the development of semiconductor radiation detectors. A semiconductor radiation detector is a solid-state version of a gaseous ionization chamber. It is simply a reverse biased p-n junction diode. In these diodes, ionizing radiations produce electron-hole pairs in the depletion region. This process is just like creation of electron-ion pairs in ionization chamber. These pairs are collected by the electric field applied and thus the detector gives an electric pulse. The amplitude of this pulse is proportional to the energy of ionizing radiation. Since semiconductor detector is a reverse biased, therefore, the signal is much larger than the noise due to leakage current.

A semiconductor material can be used as a radiation detector if it satisfies certain requirements. Some of the important requirements are:

(a) It should have low value for average energy required to create an electron-hole pair.
(b) The statistical fluctuations in the number of electron-hole pairs created for given energy should be small.
(c) Under the applied electric field charge carriers must move rapidly to the respective electrode.
(d) The number of charge carriers lost during their movement to the respective electrode should be as small as possible.
(e) The material should be able to withstand large electric fields applied across the depletion region.

The electronic structure of semiconductors is such that, at ordinary temperatures, nearly all electrons are tied to specific sites in the crystalline lattice and are occupying the valence band. At any given time, a few electrons gain sufficient thermal energy to break loose from localized sites in the valence band and shift to conduction band and are called *conduction electrons*. Since some energy must be expended in freeing an electron from its normal place in the covalent lattice of a crystal as there is a band gap that separates bound valence electrons from free conduction electrons (see Figure 7.16). In pure crystals no electrons can have energy within this gap. In silicon the band gap is about 1.1 eV, and in germanium it is about 0.7 eV. In perfect materials held at absolute zero temperature, all electrons are theoretically bound to specific lattice sites, so that the valence band is completely filled and the conduction band is empty. The thermal energy available at ordinary temperatures allows some electrons to be freed from specific sites and be elevated across the band gap to the conduction band. Therefore, for each conduction electron that exists, an electron is missing from a normally occupied valence site. This electron vacancy is called a *hole*, and in many ways it behaves as though it is a point positive charge. If an electron jumps from a nearby bond to fill the vacancy, the hole can be thought of as moving in the opposite direction. Both electrons in the conduction band and holes in the valence band can be made to drift in a preferred direction under the influence of an electric field.

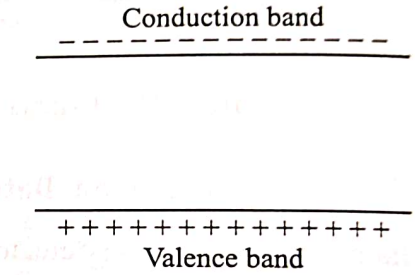

Figure 7.16 Energy gap between conduction and valence band for silicon. −sign indicates electrons and +sign indicates holes.

In semiconductor detectors, an electric field is present throughout the active volume, i.e. the volume of the detector or total volume of the depletion region, where incident radiations are detected. The subsequent drift of the electrons and holes toward electrodes on the surface of the semiconductor material generates a current pulse, in much the same manner as the motion of ion-pairs in a gas-filled ion chamber.

The minimum energy required for the creation of an electron-hole pair is the band-gap energy of about 1 eV. Experimental measurements show that, as in the production of an ion-pair in a gas, about three times the minimum energy is required on the average to form an

electron-hole pair. Thus, a 1-MeV charged particle losing all its energy in a semiconductor creates about 3,00,000 electron-hole pairs. This number is about 10 times larger than the number of ion-pairs that would be formed by the same particle in a gas. As a consequence, the charge packet for equivalent energy loss by the incident particle is 10 times larger, thus improving the signal-to-noise ratio as compared with a pulse-type ion chamber. More significant is the improvement in energy resolution. The statistical fluctuations in the number of charge carriers per pulse (that often limit energy resolution) become a smaller fraction as the total number of carriers increases. Thus, semiconductor detectors offer the best energy resolution provided by common detectors, and values of a few tenths of a per cent are not uncommon.

Another benefit is derived from the fact that the detection medium is a solid rather than a gas. In solids, the range of heavy charged particles such as alphas is only tens or hundreds of micrometers, as opposed to a few centimetres in atmospheric pressure gases. Therefore, the full energy of the particle can be absorbed in a relatively thin detector. More importantly, it is practical to fully absorb fast electrons such as beta particles. As opposed to ranges of metres in gases, fast electrons travel only a few millimetres in solids, and semiconductor detectors can be fabricated that are thicker than this range. Therefore, spectroscopic methods can be employed to measure the energies of fast electrons.

Semiconductor detectors offer many advantages over scintillation or gas-filled detectors. Some of the advantages are:

1. Excellent energy resolution.
2. Linear response over wide-energy range of incident radiation.
3. These detectors are generally compact and are small in size.
4. These detectors are fast detectors. The mobility of electrons is about 1500 cm^2/V s and the mobility of holes is about 500 cm^2/V s, which is much faster compared to mobility ions in gas counters.
5. These detectors can be fabricated in a wide range of sensitive depth and geometry.

Initially, these detectors were developed for detection of heavy charged particles. Later on, with the advancement in semiconductor technology, detectors were developed for detection of electrons, X- and γ-rays. Let us discuss some commonly used semiconductor detectors in detail.